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The Magnet Test Analysis Group

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Quench Characteristics of 5-cm-Aperture, 15-m-Long SSC Dipole Magnet Prototypes*

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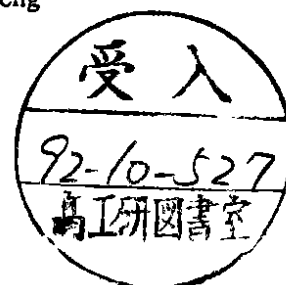
ABSTRACT

The quench performance and ramp rate sensitivity of eighteen 5-cm-aperture, 15-m-long SSC dipole magnet prototypes are discussed. All the magnets appear to reach a quench plateau near their extrapolated short sample current limit and well in excess of the operating current with very little training. Most of the magnets, however, exhibit a dramatic degradation of their quench current as a function of ramp rate, which for the most part, can be attributed to large cable eddy currents.

INTRODUCTION

Over the last year and half, eighteen 5-cm-aperture, 15-m-long SSC dipole magnet prototypes have been produced and cold-tested at Brookhaven National Laboratory (BNL) and Fermi National Accelerator Laboratory (FNAL) under contract with the Superconducting Supercollider Laboratory (SSCL). These magnets are part of an R&D program aimed at demonstrating the feasibility of the superconducting magnets for the SSC. They are also used to transfer technology from the National Laboratories to the dipole magnet contractors. Seven of the FNAL-design magnets (magnets DCA313 through DCA319) were assembled at FNAL by personnel from General Dynamics (GD), and five BNL-design magnets (magnets DCA209 through DCA213) were assembled at BNL by personnel from Westinghouse Electric Corporation (WEC). GD and WEC are respectively the leader and the follower of the collider dipole magnet contract. Five of these industrially-assembled dipole magnet prototypes, along with a quadrupole magnet prototype and a spool piece, were used in a string test recently performed at SSCL. There, the current was successfully ramped to 6520 A without any spontaneous quenching.[1]

The BNL and FNAL mechanical designs both rely on a tight clamping of the collared-coil assembly by the yoke in order to support the radial and axial components of the Lorentz force during energization, but they differ in the way this clamping is realized.[2] For the BNL magnets, the yoke is split horizontally and the clamping results from a positive collar-yoke interference along the vertical diameter, while, for the FNAL magnets, the yoke is split vertically and the clamping results from a positive collar-yoke interference along the horizontal diameter. Details on the design and mechanical performance of these magnets can be found in reference 3.

In this paper, we review the quench performance of the eighteen prototypes cold-tested so far, and we describe how it is affected by the current ramp rate.

QUENCH PERFORMANCE

Generic Test Sequence

With the exception of BNL magnets DCA208 and DCA211, all the magnets were tested following the same run plan. The run plan calls for two testing cycles, separated by a warm-up to room temperature. The first cycle includes quench testing at 4.35 K and ramp-rate study. The second cycle includes quench testing at 4.35 K, 3.85 K, and 3.5 K. Due to schedule constraints, magnet DCA208 was tested only at 4.35 K, while magnet DCA211 experienced an external bus failure during the first testing cycle. The bus is now repaired and the magnet is awaiting its second testing cycle.

BNL Magnets

Figure 1(a) presents a summary of the quench performance at 4.35 K of the BNL magnets. All the magnets reached 6600 A (the operating current of the SSC main ring) without quenching. Magnet DCA213 went directly to plateau, while the other magnets exhibited one or two training quenches. For magnets DCA207 and DCA208, the training quench currents were all above 7300 A. For magnets DCA209, DCA210, and DCA212, they were all above 7100 A. The lowest training quench is that of magnet DCA211 which occurred at 6692 A.

The determination of the training quench origins is complicated by the fact that some of them started between turn 1 and turn 13 of the inner coils, where there are no voltage taps (the turns are counted starting from the coil midplane). The second quench of magnet DCA207 originated at the lead end of lower inner coil turn 15 (the *lead end* is the magnet end where the current leads are located). The first and second
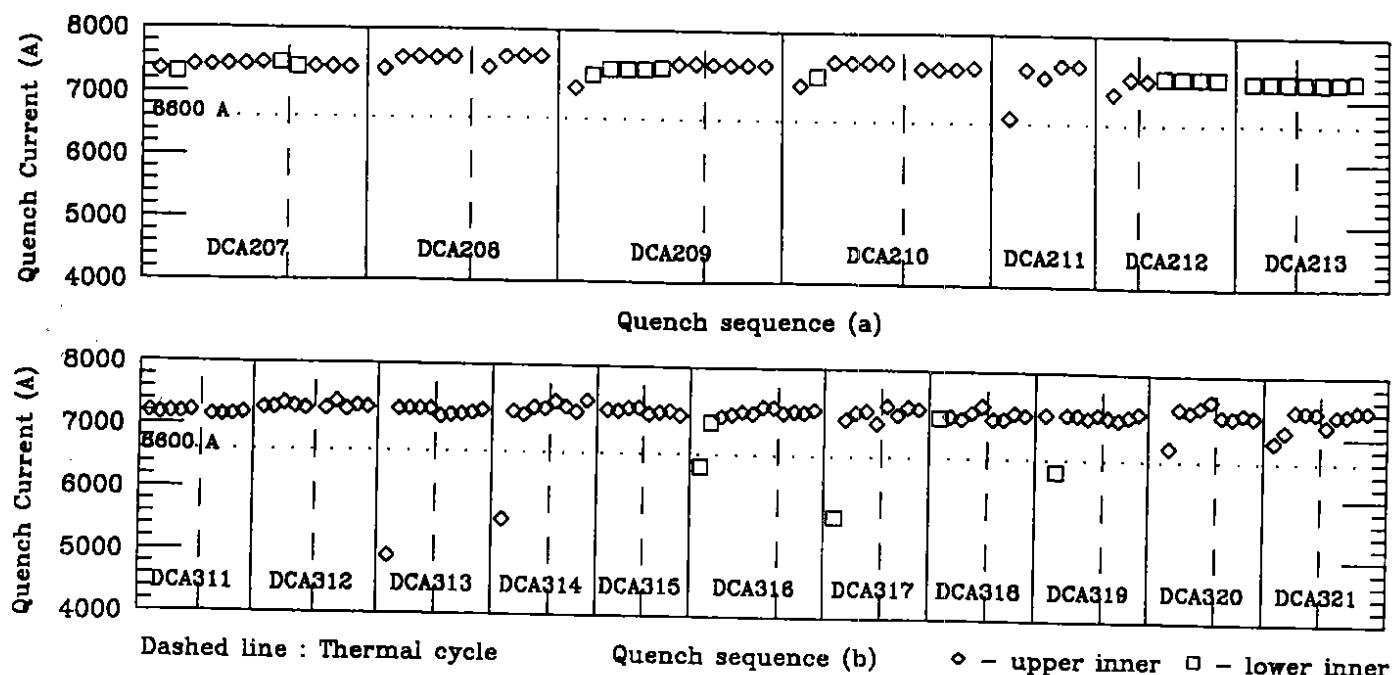
Figure. 1. Quench performance at 4.35 K of SSC dipole magnet prototypes: (a) BNL-design, and (b) FNAL-design magnets.

quenches of magnet DCA210, originated in the straight sections of upper inner coil turn 16 and lower inner coil turn 19. The first quench of magnet DCA212, originated at the non-lead end of upper inner coil turn 18. All the other training quenches originated in the multi-turn section.

All the plateau quenches started in the inner coil pole turn (turn 19), where the magnetic field is the largest. The plateau currents were all within 1% of the extrapolated short sample current limit. Note, however, the peculiar behavior of magnet DCA209. Quenches 1 to 6 were taken at 4 A/s (the nominal ramp rate of the SSC main ring), and they all originated between turn 1 and turn 13 of the inner coil. Starting with quench 7, the ramp rate was lowered to 1 A/s. As a result, the current went up by about 80 A, and the quench origin shifted to the inner coil pole turn. This extreme sensitivity on the ramp rate will be discussed in the next section.

The only magnet to exhibit re-training after a thermal cycle to room temperature was magnet DCA208, with a quench at 7407 A. The quench performance at low temperature was also quite satisfactory, with magnets DCA207 and DCA212 going directly to plateau at both 3.85 K and 3.5 K, and magnets DCA209, DCA210, and DCA213 requiring only one or two training quenches.

FNAL Magnets

Figure 1(b) presents a summary of the quench performance at 4.35 K of the FNAL magnets. Four of the magnets (magnets DCA313, DCA314, DCA316, and DCA317) exhibited a training quench below 6600 A. Magnets DCA320 and DCA321 also exhibited one or two training quenches, but they were all above 6600 A. The five remaining magnets reached a current very near the extrapolated short sample current limit on their first quench.

The low-current training quenches of magnets DCA313, DCA314, and DCA317 are very similar: they all originated toward the lead end of the inner coil pole turn, on the side opposite to the ramp-splice between the inner and outer coils. This axial location corresponds to the boundary between the last collar pack of the magnet body and the collet assembly that supports the coil end.[2] It also corresponds to the extremity of a G10 spacer, called the pole key, that supports the coil turnaround from the inside. The pole key, originally designed as a single piece, was, in these magnets, made of two pieces to facilitate assembly. It is believed that these three quenches resulted from movement of these various parts into a more stable position. After the first quenches, however, the three magnets went above 7250 A, and the problem did not resurface.

The first quench of magnet DCA316 was taken at 16 A/s and occurred at 6410 A between turn 1 and turn 13 of the inner coil. Subsequently, the magnet exhibited a behavior quite similar to that of BNL magnet DCA209. Quenches 4 to 6 were taken at 4 A/s and all originated between turn 1 and turn 13 of the inner coil. Starting with quench 7, the ramp rate was lowered to 1 A/s. As a result, the quench current went up by 100 A, and the quench origin shifted to the inner coil pole turn. Magnet DCA318 also exhibited an increase in quench current and a shift in quench localization when the ramp rate was lowered from 4 A/s (quenches 1 to 3) to 1 A/s (quenches after, and including, quench 4). The first quench of magnet DCA319 was close to the short sample current limit and originated in the inner coil pole turn, but its second quench occurred at 6415 A between turn 1 and turn 13 of the inner coil. Once again, this discrepancy can be related to a ramp-rate change: the first quench was approached at 1 A/s while the second quench occurred at 16 A/s. As we shall see in the next

section, BNL magnet DCA209 and FNAL magnets DCA316, DCA318, and DCA319 use inner cables made with strands coming from the same production batch of the same strand manufacturer.

As we already mentioned, the training quenches of magnets DCA320 and DCA321 were both above 6600 A. The first quenches of these two magnets originated between turn 1 and turn 13 of the inner coil (and were taken at 4 A/s), while the second quench of magnet DCA321 originated at the lead end of the upper inner coil pole turn (and was taken at 1 A/s).

The plateaus of the FNAL magnets appear somewhat less stable than those of the BNL magnets, but these fluctuations in the quench current result from temperature fluctuations. The only magnet to exhibit re-training after a thermal cycle to room temperature is magnet DCA321, with a quench at 7207 A. With the exception of magnet DCA314, all the magnets reached a plateau at both 3.85 K and 3.5 K in one or two training steps. Magnet DCA314 performed well at 3.85 K, but it did not sustain a stable plateau at 3.5 K.

RAMP RATE SENSITIVITY

When the current in a superconducting magnet is changed, heat is generated by several mechanisms: hysteresis in the superconductor and in the iron yoke, eddy currents flowing within individual cable strands, and eddy currents flowing from strand to strand. The resultant temperature increase causes a decrease in the plateau current of the magnet.

Figures 2(a) and 2(b) show the decrease in quench current versus ramp rate for selected BNL and FNAL magnet prototypes. The magnets in Figs. 2(a) and 2(b) have been grouped according to the manufacturer and the production batch of the strands used in their inner cables. It appears that, for the magnets of Fig. 2(a), the quench current remains roughly constant for ramp rates up to 25 A/s, above which, it starts to decrease quasi-linearly as a function of ramp rate. The worst case is magnet DCA312, which, at 200 A/s, quenches at about 2180 A, corresponding to 30% of its initial quench current. In comparison, the behavior of the magnets in Fig. 2(b) is quite different. The quench current starts by dropping significantly at low ramp rates, while the degradation at large ramp rates is much milder. The worst case is magnet DCA319, for which the quench current decreases from 7334 A at 1 A/s to 6156 A at 25 A/s, but is still of the order of 5000 A at 250 A/s. The magnets which are not included in Figs. 2(a) and 2(b) are using inner cables made with strands coming from different strand manufacturers or different production batches.

For all the magnets of Figs. 2(a) and 2(b), the plateau quenches at 1 A/s originated in the inner coil pole turn, where the field is the largest. For the magnets of Fig. 2(a), the quenches kept originating in the inner coil pole turn for ramp rates up to 25 A/s. For rates larger than 50 A/s, however, the quench origin shifted towards the inner coil midplane, between turn 1 and turn 13, where there are no voltage taps. On the other hand, for the magnets of Fig. 2(b), and as we described in the previous section, the shift in quench start localization from the inner coil pole turn to the multi-turn section occurred much sooner –between 1 A/s and 4 A/s– and was concomitant
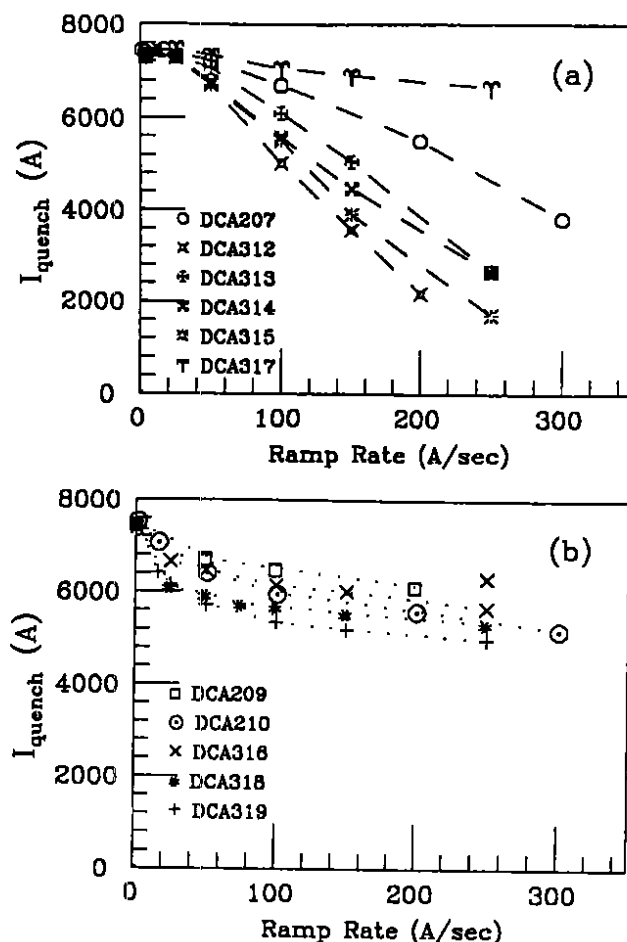

Figure 2. Ramp rate sensitivity of SSC dipole magnet prototypes. The magnets are grouped according to the manufacturer and the production batch of their inner cable strands.

to the sudden drop in quench current. Such a shift is consistent with what can be expected from the effects of cable eddy currents, which are larger towards the coil midplane, where the flux lines are perpendicular to the wide face of the cable.

In addition to quench testing at high ramp rates, AC-loss measurements were performed on most of the FNAL magnets[4] and on one of the BNL magnets (magnet DCA213).[5] The measurements were made electrically, using a simple sawtooth ramp between 500 A and 5000 A, with ramp rates varying from 30 to 150 A/s. For a given magnet, the energy loss per cycle appears to increase quasi-linearly as a function of ramp rate. Comparing the magnets with one another, it appears, that, for large ramp rates, there is a good correlation between the slope of the energy loss per cycle as a function of ramp rate and the slope of the quench current as a function of ramp rate. In other words, the magnets exhibiting the most dramatic quench degradation at large ramp rates are also the magnets exhibiting the largest AC losses. This consistency in the data indicates that both effects presumably result from the same cause, and that this cause is presumably cable eddy currents.

The next step is to try to determine the nature of these eddy currents. The inner (outer) cables used in SSC magnets consist of 30 (36) bare strands, twisted together, and shaped

into a flat, two-layer, slightly keystoned cable.[6] The cable mid-thickness is smaller than twice the strand diameter, and the contact surfaces at the crossovers between the strands of the two layers are relatively large. Also, during magnet assembly the coils are pre-compressed azimuthally.[3] Large pressures are thus applied perpendicularly to the cables, which keep the strands firmly in contact. The large contact surfaces and high pressures eventually result in low contact resistances at the strand crossovers, which couple the cable strands. Loops are thus formed where significant eddy currents can take place when subjected to a varying field.

Assuming that the eddy currents flowing from one strand to the other always pass through the crossover resistance, the cable can be represented as a simple model circuit.[7] Combining this model circuit with a two dimensional field calculation allows one to compute the cable eddy currents. The eddy-current loss can then be determined by integrating the power dissipated by the eddy currents in the crossover resistances.[8] Assuming that the crossover resistance, r_c, is uniform throughout the coil, the power, W, dissipated by the eddy currents over 1 m of SSC 5-cm-aperture dipole magnet can be estimated to be[9]

$$W = 2.5 \times 10^{-3} \, (dI/dt)^2/r_c \quad , \tag{1}$$

where W is in W/m, r_c is in $\mu\Omega$, and $\partial I/\partial t$ is the ramp rate expressed in A/s. Hence, the total energy loss, E, over a 15-m-long magnet and a monopolar current cycle from 500 A to 5000 A to 500 A can be estimated to be

$$E = 340. \, (dI/dt)/r_c \quad , \tag{2}$$

where E is in J/cycle.

Using Eq. (2) and the slopes of the energy loss per cycle as a function of ramp rate obtained experimentally, it is then possible to estimate the values of crossover resistances that are required to produce the observed effects. For the magnets of Fig. 2(a) on which AC loss measurements were performed (magnets DCA312, DCA314, and DCA315), the estimated crossover resistances are all below 10 $\mu\Omega$, while for the two magnets of Fig. 2(b) that were measured (magnets DCA318 and DCA319), r_c turns out to be of the order of 30 $\mu\Omega$.

Little is known on what determines the value of the cross-over resistance in the case of bare-strand cables like the SSC cable. It is believed to depend on the thickness of the copper oxide layer that develops around the cable strands during the various steps of cable manufacturing and magnet assembly. A particularity of the SSC strands is that they are using high purity copper (RRR $\geq$ 300), and that they are not heat-treated after the final drawing. The RRR of the as-received cables are measured to be of the order of 30. During magnet assembly, the coils are cured for some length of time at temperatures in excess of 400 K and under pressures in excess 70 MPa. The RRR of the final coils are measured to be between 100 and 200. Speculations are that the curing cycle is accompanied by a strong annealing of the conductor, and that the parameters of this cycle strongly affects the development of the copper oxide layer. (It is also interesting to note that the only difference between magnet DCA317 and the other FNAL magnets of Fig.

2(a), is that it was collared twice, and that the delay between the coil curing and the final collaring was of the order of 120 days, compared to less than 50 days for the other magnets.)

The crossover resistance model seems to provide a reasonable basis for explaining the magnet behavior at large ramp rates. So far, however, we cannot explain the low ramp rate behavior of the magnets in Fig. 2(b), and why they behave differently from the magnets of Fig. 2(a).

The issue of ramp rate sensitivity is of particular relevance for the SSC High Energy Booster, which uses a nominal ramp rate of the order of 70 A/s. It is worth mentioning, however, that FNAL magnets DCA312, DCA313, DCA314, and DCA315 exhibited anomalous behavior of their magnetic field harmonics during current ramp at 4 A/s.[8,10] These anomalies, which cease when the current ramp is stopped, can also be explained in terms of eddy currents.[8]

CONCLUSION

The quench performance of the eighteen BNL-design and FNAL-design 5-cm-aperture, 15-m-long SSC dipole magnet prototypes cold-tested so far appears to be quite satisfactory, with only 4 training quenches below the operating current of the SSC main ring. Three of these four quenches are attributed to a design flaw in a coil end support piece, which has now been corrected. Magnets of the two designs, however, exhibit a dramatic decrease of their quench current as a function of ramp rate. This poor AC behavior can, for the most part, be attributed to large cable eddy currents. Efforts are now under way to confirm the nature of these eddy currents and determine the cable parameters that need to be mastered to control them.

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